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Axial Detonator for Simultaneous Ignition of Multiple HE Points

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DISCLAIMER

AXIAL DETONATOR FOR SIMULTANEOUS IGNITION OF MULTIPLE HE POINTS*

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ABSTRACT

We have designed and tested an axial detonator, 2.54 cm in diameter and constructed of 2.54-cm-long modules, that simultaneously ignites many points on the axis of a long cylinder of high explosive, which in turn uniformly expands a metal cylinder. Detonators containing up to 47 modules have been successfully tested with an RMS deviation of 0.04 to 0.05 μs.

INTRODUCTION

The axial detonator is a 2.54-cm-diam system constructed from 2.54-cm-long modules. Its purpose is to simultaneously ignite many points on the axis of a long cylinder of high explosive (HE) so that the HE can, in turn, uniformly expand a metal cylinder. Most tests of the system have been done using 7, 25, and 47 units; theoretically, however, any number of units could be used. Here we present the theoretical calculations for this type of detonator and the experimental results of test firings, both with and without the additional HE.

THEORETICAL ANALYSIS

Detonator Spacing

Design of the axial detonator began by determining the optimum detonator spacing. Too few detonators would produce unacceptably large nonuniformities in the expanding cylinder; too many would be impractical or too expensive. Several computer runs were made with a two-dimensional hydrodynamics code for a cylindrical system with 14-cm-radius HE 9404, 6 mm of Lucite, and 6.4 mm of copper. Detonator spacings of 1.27, 2.54, and 5.08 cm were tried.

The 1.27-cm-spacing gave a peak-to-trough ripple of 20 μm in the outer radius of the copper tube. The 2.54-cm spacing gave 200 μm, and the 5.08-cm spacing gave 2.54 mm. Because the accuracy of the wall thickness of the copper tube was limited to about 200 μm, a 2.54-cm spacing was chosen. In addition to these runs, several one- and two-dimensional code runs were made to ascertain whether this system would spall. In the system are described above, spalling did not appear to be serious, but in a smaller system (3.81-cm outer copper radius), it was. Consequently, all the experimental tests were done on the large HE system described.

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Electrical Circuit Analysis

For symmetry, a three-lead system was chosen. The system for a seven-unit detonator is illustrated in Fig. 1. This system was built with bridgewires (BW) only and test fired. Results showed that the greater the distance of a BW from the center BW, the earlier it fired. This phenomenon was symmetrical about the center BW.

In general, let $M_{uv\text{-}xy}$ be the mutual inductance between any element of line uv acting on any adjacent element in line xy. Specifically, assume that $M_{ab\text{-}ef} = M_{ef\text{-}ab} = M_{cd\text{-}ab} = M_{cd\text{-}ef}$, etc. $= M_x$, and that only adjacent elements couple. (See Fig. 2 for the three-dimensional layout of the lines ab, cd, and ef.) Then the voltage across path abcehf is

$$q/C + (6L_x)(7\dot{I}) + L_{bc}(7\dot{I}) + L_3\dot{I} + L_x(1 + 2 + 3 + 4 + 5 + 6)\,\dot{I}$$
$$- (6M_{ab\text{-}ef})(7\dot{I}) - 21M_{ef\text{-}ab}\dot{I} - 21M_{cd\text{-}ab}\dot{I} + 21M_{cd\text{-}ef}\dot{I} = 0 \,, \qquad (1)$$

where L_{bc} is the self-inductance of the turnaround line bc. Equation (1) reduces to

$$q/C + 42L_x\dot{I} + 7L_{bc}\dot{I} + L_3\dot{I} + 21L_x\dot{I} - 63M_x\dot{I} = 0 \,. \qquad (2)$$

A similar relationship holds for path abcghf:

$$q/C + (6L_x)(7\dot{I}) + L_{bc}(7\dot{I}) + L_0\dot{I} + L_x(30\dot{I}) - (6M_{ab\text{-}cf})(7\dot{I})$$
$$- 30M_{cf\text{-}ab}\dot{I} - 12M_{ed\text{-}ab}\dot{I} + 12M_{ed\text{-}cf}\dot{I} = 0 \,. \qquad (3)$$

This reduces to

$$q/C + 42L_x\dot{I} + L_{bc}(7\dot{I}) + L_0\dot{I} + 30L_x\dot{I} - 72M_x\dot{I} = 0 \,. \qquad (4)$$

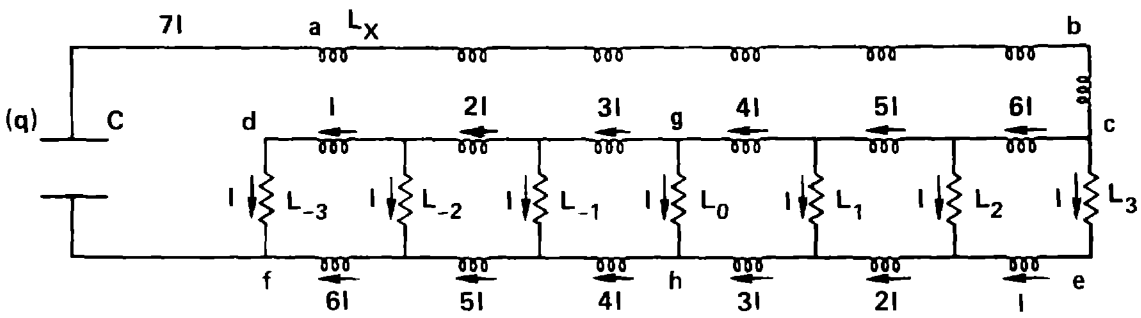
Equating Eqs. (2) and (4) yields

$$L_3 = L_0 + 9L_x - 9M_x = L_0 + 3^2(L_x - M_x) \,. \qquad (5)$$

A general formula can be deduced:

$$L_{\pm n} = L_0 + n^2(L_x - M_x),\ n = 0, 1, 2, 3, \ldots \qquad (6)$$

This means that individual additional inductances have to be added to each path to ensure detonator simultaneity. For example, in a 25-unit system, the 15th BWs from the center require an additional inductance of $L_{\pm 15} = L_0 + 225(L_x - M_x)$.



C is the capacitance of the firing unit.
q is the charge on the capacitor.
I is the current flowing through each bridgewire.
L_X is the self-inductance of each 2.54-cm-long conducting element. (Only one element is labeled in the figure.)

Fig. 1. Electrical circuitry for seven-unit detonator.

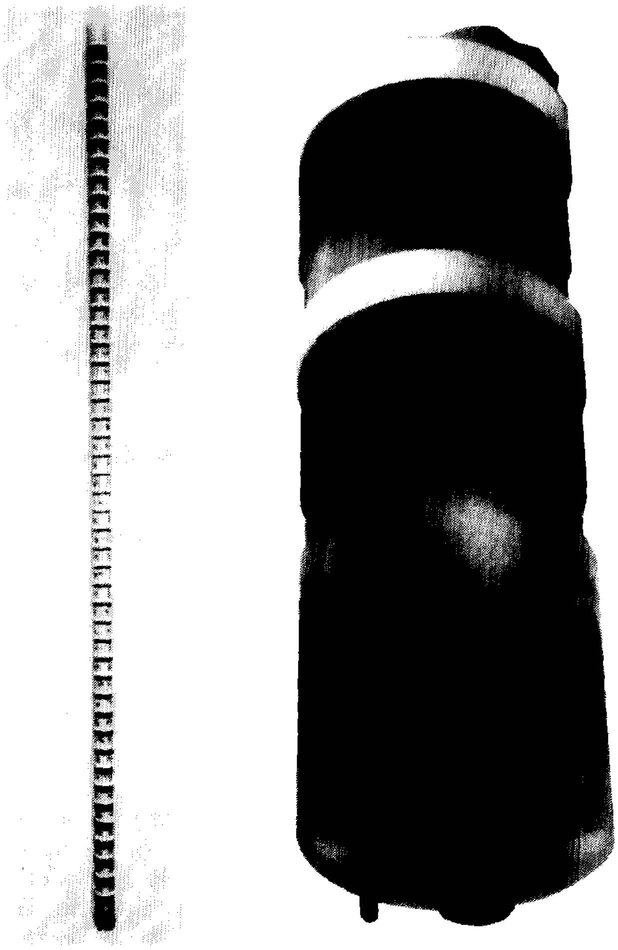


Fig. 2. Axial detonator.

The self-inductance L_x, which can be calculated from a formula given by Grover (p. 35),[1] is 0.016 μH/module spacing. The M_x, which can also be calculated by referring to Grover (p. 32),[1] is 0.004 μH/module spacing. Therefore,

$$L_{\pm n} = L_0 + n^2(0.012)\mu\text{H/module spacing} . \tag{7}$$

For No. 23 wire (diameter $\approx$ 0.635 mm) wound as a solenoid on a 2.35-cm-diam mandrel, one can calculate the inductance as a function of the number of turns (T). The formula used is given by Grover (p. 153).[1] The diameter of the coil is assumed to be the diameter of the mandrel plus the diameter of the wire, and the length of the coil is assumed to be the number of turns times the diameter of the wire. Figure 3 shows calculated and measured inductance (L) as a function of T. Using the measured curve and Eq. (7), T can be determined to give the correct additional inductance for each individual BW. The L_0 was chosen to be 0.4 μH to help isolate the central BW.

Equation (6) does not include the effects of mutual inductance between coils. Because all the additional coils are wound in the same direction on the axial detonator, the fluxes from neighboring coils will increase the flux in any individual coil. Assuming that only the immediate neighboring coils will influence any individual coil, we can recast Eq. (6) as

$$L_n = L_0 + n^2(L_x - M_x) + M_{0,1} + M_{0,-1} - M_{n,n+1} - M_{n,n-1} , \tag{8}$$

where $M_{n,n-1}$ is the mutual inductance between the n and $n-1$ coils, etc. Because $M_{0,1} = M_{0,-1}$, we have

$$L_n = 0.4 + n^2(0.012) + 2M_{0,1} - M_{n,n+1} - M_{n,n-1} . \tag{9}$$

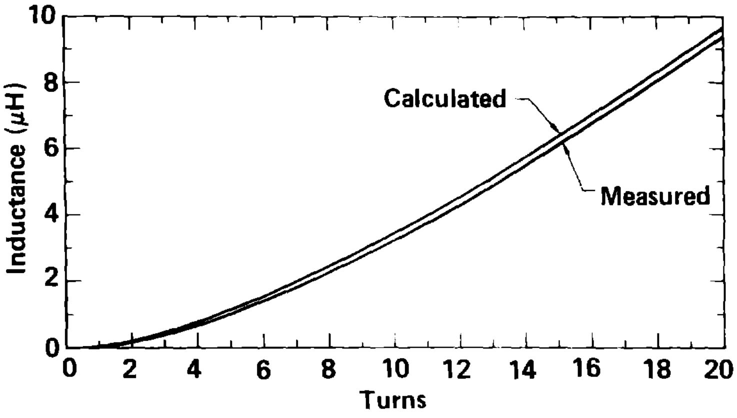


Fig. 3. Calculated and measured inductance as a function of number of turns.

The Ms are functions of L_n, therefore, an exact solution of Eq. (9) would require several iterations. However, to see how these mutuals affect L_n, one can calculate $M_{n,n-1}$ and $M_{n,n+1}$ for several values of n, using the values of L_n calculated from Eq. (7). Grover (p. 123)[1] gives a method for calculating the mutual inductances of coils in our configuration. For n = 1, 11, and 22, the values of M are given in Table 1. Comparing the values of L_n from Eqs. (7) and (9), we see that the effect of the mutuals is less than 10%. Therefore, the inductances calculated from Eq. (7) represent a reasonable first-order correction to the nonsimultaneity.

By using the additional inductances, we have experimentally achieved good simultaneity with the exception of the end units. The end coils, having only one immediate neighboring coil, will contain less flux and hence will have smaller effective inductances than they should have to ensure simultaneity. Perhaps simultaneity would be improved if the inductance for end coils was increased by about 0.4 μH (see Table 1). Alternatively, the simplest approach is to design the hydrodynamic system so that the end units are either unimportant or not used.

Shearer suggests that the effect of mutual inductance between coils could be substantially reduced if the direction of winding is reversed in alternate pairs of coils (i.e., 1 and 2 clockwise, 3 and 4 counterclockwise, 5 and 6 clockwise, etc.).[2] In this way, the fluxes from the $n - 1$ and $n + 1$ coils tend to cancel in the vicinity of the *n*th coil. In such a case, the contribution of the mutuals to the total inductance is approximately equal to $2n\mu\,(L_x - M_x)$, where μ is the coupling coefficient. In a system constructed with all coils wound in the same direction, the contribution of the mutuals to the total inductance is approximately $2n^2\mu(L_x - M_x)$. For large n, the ratio of these mutual contributions is approximately 1/n. Therefore, except for the end units, the second-order correction to the simultaneity could be made by reversing the direction of windings as suggested.

Total Inductance of the System

Let L_D be the inductance of the firing unit and associated cables; then

$$L_{total} = L_D + \frac{V_{total}}{I_{total}} . \tag{10}$$

Table 1. Mutual Inductances (μH)

n	$M_{n,n-1}$	$M_{n,n+1}$	L_n Eq. (7)	L_n Eq. (9)
1	0.0132	0.0352	0.412	0.390
11	0.0684	0.0863	1.85	1.72
22	0.355	0.402	6.20	5.48

The V_{total} is the voltage between points a and f (see Fig. 1), and $\dot{I}_{total} = N\dot{I}$, where N is the total number of BWs. To obtain V_{total}, we can generalize Eq. (1) to N units; that is,

$$V_{total} = (N-1)L_x(N\dot{I}) + L_xN\dot{I} + L_n\dot{I} + L_x\left[\sum_{j=1}^{N-1} j\right]\dot{I} - 2M_x\left[\sum_{j=1}^{N-1} j\right]\dot{I} + M_x\left[\sum_{j=1}^{N-1} j\right]\dot{I} - (N-1)M_x(N\dot{I}) \tag{11}$$

where L_{bc} has been set equal to L_x. Term five is the voltage induced in conductors ab by conductors ef and cd. Terms six and seven are the voltages induced in conductor ef by conductors cd and ab, respectively. However,

$$\sum_{j=1}^{N-1} j = \frac{N(N-1)}{2} \ . \tag{12}$$

Therefore,

$$L_{total} \equiv L_T = L_D + \frac{1}{N}\left[N(N-1)(L_x - M_x) + NL_x + L_n + \frac{N(N-1)}{2}(L_x - M_x)\right] . \tag{13}$$

Since $n = (N-1)/2$, Eq. (6) can be written

$$L_n = L_0 + \frac{(N-1)^2}{4}(L_x - M_x) \ . \tag{14}$$

Substituting this expression for L_n into Eq. (13), we obain

$$L_T = L_D + \frac{1}{N}\left[\frac{3}{2}N(N-1)(L_x - M_x) + NL_x + L_0 + \frac{(N-1)^2}{4}(L_x - M_x)\right] . \tag{15}$$

For large N, $N \approx N - 1$; $\frac{(N-1)^2}{4}(L_x - M_x) \gg L_0$ and $\frac{3}{2}N(N-1)L_x \gg NL_x$. Therefore, Eq. (15) can be reduced to the simple working relationship

$$L_T \approx L_D + \frac{7}{4}N(L_x - M_x) = L_D + 0.021N\ \mu H \ . \tag{16}$$

In general, L_D has been about 0.18 μH.

Burst-Current Calculations

To achieve good simultaneity, the current flowing through each BW at burst time I_b should be greater than the experimentally determined minimum current I_{min} necessary to blow up the BW. For a capacitor-bank unit, the current I flowing through any BW can be represented by

$$I(t) = I_{max} \sin \omega t \ , \tag{17}$$

where t is time in μs and ω represents frequency in radians/μs. Let

$$G = \int_0^{t_b} I_{max}^2 \sin^2 \omega t \, dt = I_{max}^2\left(\frac{t_b}{2} - \frac{\sin 2\omega t_b}{4\omega}\right) , \tag{18}$$

where t_b is the time when the BW bursts. Then

$$\frac{2G}{I_{max}^2} = t_b - \frac{\sin 2\omega t_b}{2\omega} \ . \tag{19}$$

However,

$$\omega \approx (L_T C)^{-1/2} , \tag{20}$$

and the maximum current flowing through each BW is

$$I_{max} \approx \left(\frac{C}{L_T}\right)^{1/2} \frac{V}{N} , \tag{21}$$

where V is the voltage on the capacitor. Therefore,

$$\frac{2GL_T N^2}{CV^2} = t_b - \frac{\sin 2t_b (L_T C)^{-1/2}}{2(L_T C)^{-1/2}} . \tag{22}$$

Tucker[3] has tabulated measured values of I_{min} and the action integral G for a number of detonators using gold BWs 1-mm long and 38 μm in diameter. From these, reasonable values of G and I_{min} applicable to these calculations can be determined. Therefore, for a given system (N, L_T) and capacitor-bank unit (C, V), t_b can be determined. Then I_b can be determined from Eq. (17). For example, consider a bank with C = 14.7 μF charged to 8.5 kV as a possible firing unit for a 47-unit system. From Eq. (16), $L_T \approx 1.2$ μH; G = 0.12 $A^2 \cdot s$. Then, t_b = 2.58 μs and I_b = 365 A. Because this type of calculation does not include resistance, I_b will be overestimated. However, because I_b is sufficiently greater than the measured value of I_{min} of 240 A, the 47 BWs should burst simultaneously.

BRIEF DESCRIPTION OF THE SYSTEM

Figure 4 illustrates the mechanical and electrical design of the system. The printed circuit board is copper plated, and then a gold BW is soldered in place. For insulation, an epoxy coating is applied to the front side of the printed circuit, except at the points of electrical contact. An annulus of 9407 is cemented to the front surface of the circuit board, and inside the annulus a PETN pellet is pressed against the BW. The 9407 and the circuit board have three holes each to allow for the electrical connecting elements. These elements are insulated with Thermofit RF tubing. The Lucite spacer and coil form is held in position by cementing it to the back surface of the next printed circuit board. Good electrical contacts are made between the 2.54-cm-long connecting elements and the circuit boards by means of shoulders on the connecting elements and the copper plating on the boards. This technique of making the connecting elements out of small copper rods that screw together also ensures that the system will be reasonably rigid. The circuit board is slightly bigger in diameter than the 9407 so that there will be no HE-on-HE contact when the detonator system is slid into a hole in a cylinder of HE. Finally, a Silastic compound is injected inside the Lucite spacer to completely seal the electrical components. Because chemicals in the Silastic have a deleterious effect on the PETN, the latter is sealed with a small Lucite disk. This disk also keeps the PETN securely pressed against the BW. Figure 2 shows the completed detonator.

EXPERIMENTAL RESULTS

Detonators Only

Three experiments performed with the Model 754 streaking camera provided the majority of information on the 47-unit system. The results from all three experiments are similar, showing a maximum spread of about 200 ns (excepting end detonators) with an RMS value, $\sigma = [\Sigma(\Delta t)^2/47]^{1/2}$, of 40 to 50 ns. In all cases, Detonator 47 (the detonator away from the firing-unit input cables) went about 300 ns early, and Detonator 1, 130 to 190 ns early. The only other difficulties in the three shots were with pair 17 and 31 (especially 31), which went 100 to 150 ns late. (There was also some minor nonsimultaneity in pair 22 and 26.) It is possible that these problems may be due to reflections in the line caused initially by having too low an inductance at the end detonators.

For a 25-unit system, σ = 15 to 20 ns and the total spread is about 95 ns. These values are about a factor of two better than those for the 47-unit system.

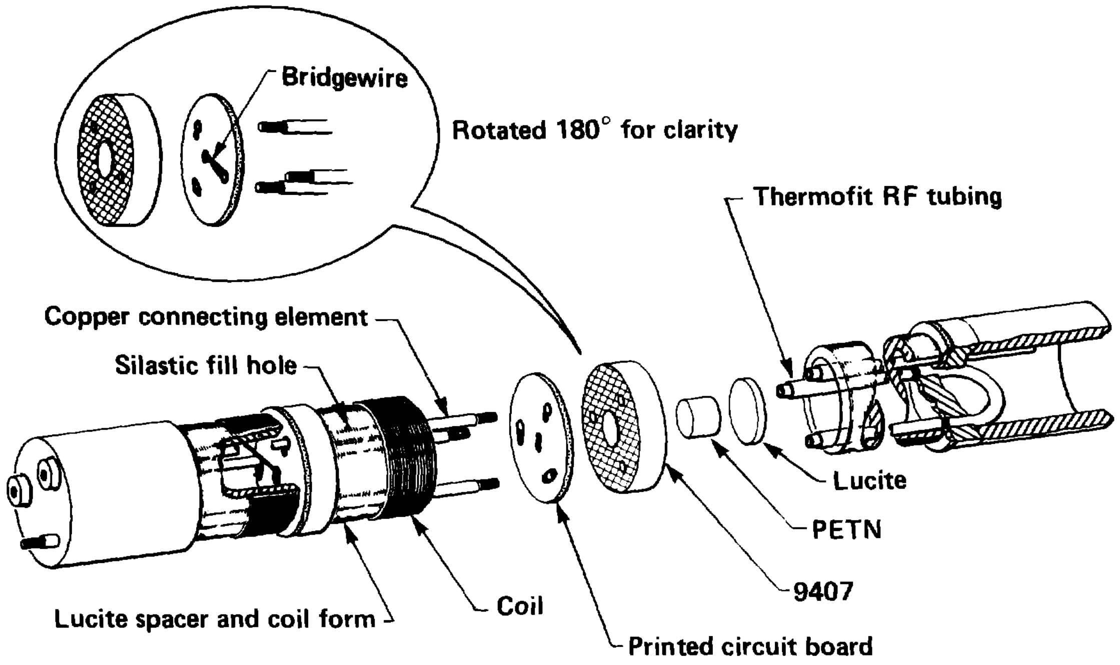


Fig. 4. Mechanical and electrical design of axial detonator system.

Detonators Used with HE and Copper Cylinders

Two experiments were performed with the 25-unit detonator and HE system described above. In the first experiment, a Model 189 record showed the final wall velocity to be 0.277 cm/μs. Model 6 records show that the cylinder could expand at least 10 cm without breaking up. (A Model 6 record of another shot showed that a 15-cm expansion was possible.) A Lucite flasher block was located parallel to the long axis of the cylinder 1.27 cm from the outside copper wall, and was viewed by a Model 754 streaking camera. The optical record showed that the average deviation in time between the wall directly above a detonator and the wall between two detonators is about 85 ns, which, with the measured wall velocity, gives a radial deviation of 230 $\pm$ 25 μm. This compares favorably with the two-dimensional calculation.

In the second experiment, pins were used to determine the degree of ellipticity in the expansion of the copper cylinder. Four sets of 39 pins were located at approximately 90° intervals; each set with pins 2.54, 5.08, and 7.62 cm from the outer copper wall. In this way, the uniformity of flatness of the wall at four positions could be checked, and the cylindrical uniformity of the whole tube could be examined by combining the results from the four positions. A Model 754 camera recorded the radius-time (R-t) history of a single point on the copper wall, but an unfortunate timing error resulted in the loss of some of the R-t history. However, what optical data were obtained agreed well with data from the previous experiment.

We determined the RMS cylindrical uniformity over the whole tube to be $\pm$90 ns (or about $\pm$230 μm). The maximum deviation in time between any two pins that should have gone simultaneously was 330 ns (two pins 7.62 cm from outer wall). The maximum deviation in time expected between two separate points on the copper cylinder is given in Table 2. This is a sum of individual maximum deviations from various asymmetries inherent in detonator construction and HE assembly. As expected, the measured maximum deviation is somewhat less than the calculated value.

Table 2. Maximum Deviation in Time Between Two Points on the Cylinder

Source	Deviation (ns)
BW orientation	59
Transmission lines being fed through 9407	49
Variation in hole diameter in main HE (25.73 to 25.81 mm)	40
Maximum difference in burst time between any two BWs (2 assemblies, σ = 20 ns)	100
Variation in copper wall thickness	80
Eccentricity of HE, plastic smoother, and copper	40
TOTAL MAXIMUM DEVIATION	368

CONCLUSIONS

Phased Detonators

This detonator system was thought to be flexible enough to produce a phased or time-staggered detonation of the individual units. This would allow the copper wall to expand at an angle greater than zero, but much less than the 12.5° angle that is achieved by simply burning the HE sideways. A 25-unit system was fired with an expected angle of 0.5°. The measured value was 0.5 ± 0.04°. A second test of a detonator alone showed that the maximum angle that could be achieved in the present 25-unit design was about 3/4°. This is because the first unit to be detonated quickly breaks the transmission line.

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2. J. Shearer, Lawrence Livermore National Laboratory, Livermore, CA, private communication (1967).
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